Computer Vision I

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Machine Learning for Computer Vision
TU Dresden

https://mlcv.cs.tu-dresden.de/courses/25-winter/cv1/

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Basic mathematical notation:

- For any finite set A, let $|A|$ denote the number of elements of A.
- For any set A, let 2^A denote the power set of A.
- For any set A and any $m \in \mathbb{N}$, let $\binom{A}{m}$ denote the set of all m-elementary subsets of A, that is, $\binom{A}{m} = \{B \in 2^A \colon |B| = m\}$.
- For any sets A, B, let B^A denote the set of all maps from A to B.
- For any $f \in B^A$, any $a \in A$ and any $b \in B$, we may write $b = f(a)$ or $b = f_a$ instead of $(a, b) \in f$
- Let $\langle \cdot, \cdot \rangle$ denote the standard inner product, and let $\| \cdot \|$ denote the l_2-norm.
- We identify any natural number $m \in \mathbb{N}$ with the set $m = \{0, \ldots, m-1\}$. In particular, we may write $j \in m$ instead of $j \in \{0, \ldots, m-1\}$.

Definition 1. For any $n_0, n_1 \in \mathbb{N}$ and any $C \neq \emptyset$, a map $f \in C^{n_0 \times n_1}$ is called a **digital image**, and a map $f \in C^{\mathbb{Z} \times \mathbb{Z}}$ is called an **infinite digital image**.

In both cases, n_0, n_1 are called the **width** and **height** of the image, and C is called its **color set**. The elements of $n_0 \times n_1$ are called the **pixels** of the image. The graph $G = (V, E)$ with $V = n_0 \times n_1$ and such that $\forall r, r' \in V \colon \{r, r'\} \in E \Leftrightarrow \|r - r'\| = 1$ is called its **pixel grid graph**.

Examples.

Gray levels	$C = \{0, \ldots, 255\}$
RGB colors	$C = \{0, \ldots, 255\}^3$
Real numbers	E.g. $C = \mathbb{R}$ or $C = [0, 1]$
Real tuples	E.g. $C = \mathbb{R}^n$ or $C = [0, 1]^n$

Definition 2. For any $n_0, n_1 \in \mathbb{N}$ and any set $C \neq \emptyset$, a **point operator** on digital images of width n_0, height n_1 and with color set C is a function

$$\varphi \colon C^{n_0 \times n_1} \to C^{n_0 \times n_1} \tag{1}$$

such that there exists a function

$$\chi \colon C \times n_0 \times n_1 \to C \tag{2}$$

such that for every digital image $f \in C^{n_0 \times n_1}$ and every pixel $(x, y) \in n_0 \times n_1$:

$$\varphi(f)(x, y) = \chi(f(x, y), x, y) \ . \tag{3}$$

Remark. The color $\varphi(f)(x, y)$ of the image $\varphi(f)$ at the pixel (x, y) depends only on the color $f(x, y)$ of the image f at that same pixel, and on the pixel coordinates, x and y.

Example. Every $\xi \colon C \to C$ defines a point operator, namely $\varphi_\xi \colon f \mapsto \xi \circ f$.

Definition 3. Let $C = [0,1]$. For any $\gamma \in (0,\infty)$ and the function $\xi\colon C \to C : c \mapsto c^\gamma$, the point operator $\varphi_\xi\colon f \mapsto \xi \circ f$ is called the **gamma operator**.

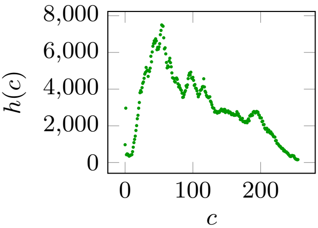
$\gamma = \frac{1}{4}$ $\quad$ $\gamma = \frac{1}{2}$ $\quad$ $\gamma = 1$ $\quad$ $\gamma = 2$ $\quad$ $\gamma = 4$

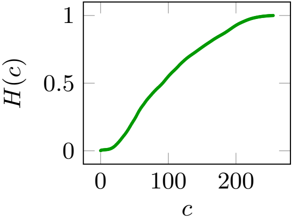
Definition 4. The **histogram** of a digital image $f\colon n_0 \times n_1 \to C \subseteq \mathbb{R}$ is the function $h\colon C \to \mathbb{N}_0$ such that for any $c \in C$:

$$h(c) = |\{r \in n_0 \times n_1 \mid f(r) = c\}| \tag{4}$$

The **cumulative distribution of colors** is the function $H\colon C \to [0,1]$ such that for any $c \in C$:

$$H(c) = \frac{1}{n_0\, n_1} \sum_{\substack{c' \in f(n_0 \times n_1) \\ c' \leq c}} h(c) \tag{5}$$





Histogram equilibration

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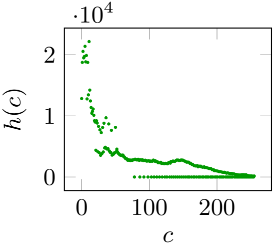
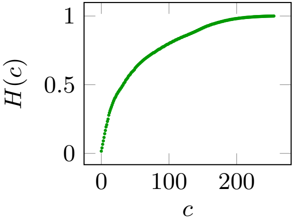




Definition 5. For any $C = [c^-, c^+] \subseteq \mathbb{R}$ and any monotonous function $H\colon C \to [0,1]$ such that $H(c^+) = 1$, H-**equilibration** is the function

$$\begin{aligned} \xi_H\colon \quad [c^-, c^+] &\to [c^-, c^+] \\ c &\mapsto c^- + (c^+ - c^-)\, H(c) \end{aligned}$$

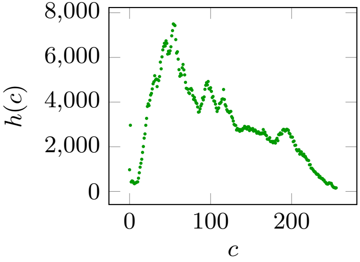
For fixed H and fixed $n_0, n_1 \in \mathbb{N}$, H-equilibration defines a point operator that we call the H-**equilibrator**:

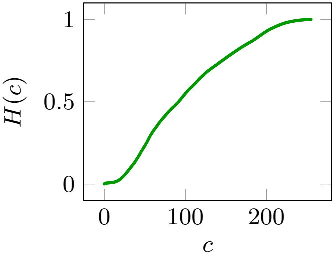
$$\begin{aligned} \varphi_{\xi_H}\colon \quad C^{n_0 \times n_1} &\to C^{n_0 \times n_1} \\ f &\mapsto \xi_H \circ f \end{aligned}$$

For any digital image f with the cumulative distribution H of colors C, we call the image $\varphi_{\xi_H}(f)$ the **self-equilibration of** f.

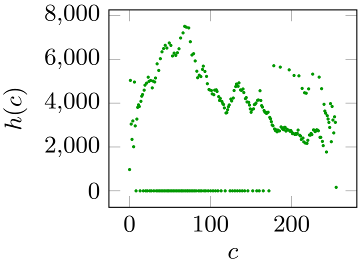
Question. Is self-equilibration a point operator?

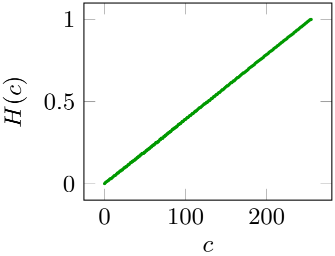
Histogram equilibration





Histogram equilibration

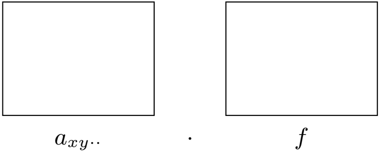




An operator $\varphi\colon \mathbb{R}^{n_0 \times n_1} \to \mathbb{R}^{n_0 \times n_1}$ is **linear** if and only if there exists $a\colon (n_0 \times n_1)^2 \to \mathbb{R}$ such that for any (image) $f \in \mathbb{R}^{n_0 \times n_1}$ and any (pixel) $(x, y) \in n_0 \times n_1$:

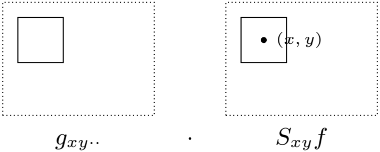
$$\varphi(f)(x,y) = \sum_{j=0}^{n_0-1} \sum_{k=0}^{n_1-1} a_{xyjk}\, f(j,k) \ . \tag{6}$$

$\varphi(f)(x,y) \quad =$



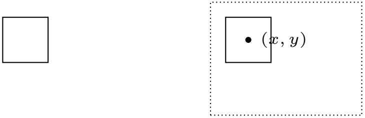
More restrictive than such an operator with $(n_0 n_1)^2$ coefficients is:

$\varphi(f)(x,y) \quad =$



Even more restrictive is the typical setting in which we are given $m_0, m_1 \in \mathbb{N}$ and $g\colon m_0 \times m_1 \to \mathbb{R}$ and

$\varphi(f)(x, y) \quad =$



$$g \quad \cdot \quad S_{xy} f$$

$$= \quad \sum_{j=0}^{m_0-1} \sum_{k=0}^{m_1-1} g(j,k) f\left(x + j - \left\lfloor \tfrac{m_0-1}{2} \right\rfloor, y + k - \left\lfloor \tfrac{m_1-1}{2} \right\rfloor\right)$$

Remark.

1. f needs to be extended in order for $\varphi(f)$ to be well-defined.
2. g uniquely defines a linear operator φ_g.
3. Its application to images f defines a binary operation $f \otimes g := \varphi_g(f)$.
4. g itself is a digital image.

Definition 6. 1-dimensional discrete convolution is the operation $*\colon \mathbb{R}^{\mathbb{Z}} \times \mathbb{R}^{\mathbb{Z}} \to \mathbb{R}^{\mathbb{Z}}$ such that for any $f, g\colon \mathbb{Z} \to \mathbb{R}$ and any $t \in \mathbb{Z}$:

$$(f * g)(t) = \sum_{s=-\infty}^{\infty} f(t+s)\, g(-s) \ . \tag{7}$$

2-dimensional discrete convolution is the operation $*\colon \mathbb{R}^{\mathbb{Z}\times\mathbb{Z}} \times \mathbb{R}^{\mathbb{Z}\times\mathbb{Z}} \to \mathbb{R}^{\mathbb{Z}\times\mathbb{Z}}$ such that for any $f, g\colon \mathbb{Z}\times\mathbb{Z} \to \mathbb{R}$ and any $(x, y) \in \mathbb{Z}\times\mathbb{Z}$:

$$(f * g)(x, y) = \sum_{j=-\infty}^{\infty} \sum_{k=-\infty}^{\infty} f(x+j, y+k)\, g(-j, -k) \ . \tag{8}$$

Remark. The minus (in $-s$ in (7), and in $-j, -k$ in (8)) makes the operator $*$ commutative.

Lemma 1. For any $f, g, h \in \mathbb{R}^{\mathbb{Z}\times\mathbb{Z}}$ and any $\alpha \in \mathbb{R}$, we have:

$$f * g = g * f \qquad \text{(commutativity)} \tag{9}$$

$$f * (g * h) = (f * g) * h \qquad \text{(associativity)} \tag{10}$$

$$f * (g + h) = (f * g) + (f * h) \qquad \text{(distributivity)} \tag{11}$$

$$\alpha(f * g) = (\alpha f) * g \qquad \text{(associativity with } \cdot\text{)} \tag{12}$$

Definition 7. For any $C \neq \emptyset$, the map

$$X : \bigcup_{n_0, n_1 \in \mathbb{N}} C^{n_0 \times n_1} \to C^{\mathbb{Z} \times \mathbb{Z}} \tag{13}$$

such that for any $n_0, n_1 \in \mathbb{N}$, any $f\colon n_0 \times n_1 \to C$ and any $(x, y) \in \mathbb{Z}^2$:

$$X(f)(x,y) = \begin{cases} f(x,y) & \text{if } (x,y) \in n_0 \times n_1 \\ 0 & \text{otherwise} \end{cases} \tag{14}$$

is called the **infinite** 0-**extension** of digital images.

Definition 8. For any $C \neq \emptyset$ and any $n_0, n_1 \in \mathbb{N}$, the map

$$R_{n_0,n_1}\colon C^{\mathbb{Z} \times \mathbb{Z}} \to C^{n_0 \times n_1} \tag{15}$$

such that for any $f\colon \mathbb{Z} \times \mathbb{Z} \to C$ and any $(x, y) \in n_0 \times n_1$:

$$R_{n_0,n_1}(f)(x,y) = f(x,y) \tag{16}$$

is called the (n_0, n_1)-**restriction** of infinite digital images.

Definition 9. For any $j, k \in \mathbb{Z}$, the operator $S_{jk} \colon C^{\mathbb{Z}\times\mathbb{Z}} \to C^{\mathbb{Z}\times\mathbb{Z}}$ such that for any $x, y \in \mathbb{Z}$: $S_{jk}(f)(x, y) = f(x + j, y + k)$ is called the (x, y)-**shift** of infinite digital images.

Definition 10. The operator $L \colon C^{\mathbb{Z}\times\mathbb{Z}} \to C^{\mathbb{Z}\times\mathbb{Z}}$ such that for any $x, y \in \mathbb{Z}$, we have $L(f)(x, y) = f(-x, -y)$ is called the **reflection** of infinite digital images.

Definition 11. For any $n_0, n_1, m_0, m_1 \in \mathbb{N}$, any $f \in C^{n_0 \times n_1}$, any $g \in C^{m_0 \times m_1}$, $d_0 = -\left\lfloor \frac{m_0-1}{2} \right\rfloor$ and $d_1 = -\left\lfloor \frac{m_1-1}{2} \right\rfloor$, the **convolution** of f and g is defined as

$$f * g := R_{n_0 n_1}(X(f) * S_{d_0 d_1}(X(g))) \tag{17}$$

Lemma 2. For any $f, g \in C^{\mathbb{Z} \times \mathbb{Z}}$:

$$f \otimes g = f * L(g) \tag{18}$$

Definition 12. For any $\sigma \in \mathbb{R}^+$ and any $m \in \mathbb{N}_0$ (typically: $m \geq 3\sigma$), for the function

$$w\colon \quad \mathbb{R} \to \mathbb{R}\colon \quad t \mapsto e^{-\frac{t^2}{2\sigma^2}} \tag{19}$$

and the number

$$N := \sum_{j=-m}^{m} w(j) \ , \tag{20}$$

the functions

$$g_0\colon \quad (2m+1) \times 1 \to \mathbb{R}\colon \quad (x,0) \mapsto \frac{w(j-m)}{N} \tag{21}$$

$$g_1\colon \quad 1 \times (2m+1) \to \mathbb{R}\colon \quad (0,y) \mapsto \frac{w(j-m)}{N} \tag{22}$$

are called **Gaussian averaging filters**.

Linear operators

f

$f * g_0 * g_1$

$\sigma = 3.0$
$m = 9$

$f * g_0 * g_1$

$\sigma = 10.0$
$m = 30$

Linear operators

f

Linear operators

f

$2f - (f * g_0 * g_1)$

$\sigma = 1.0$
$m = 3$

Definition 13. The **discrete derivatives** of an infinite digital image $f\colon \mathbb{Z} \times \mathbb{Z} \to \mathbb{R}$ are defined as

$$\partial_0 f := g * d_0 \tag{23}$$
$$\partial_1 f := g * d_1 \tag{24}$$

with

$$d_0 = \frac{1}{2}(1, 0, -1) \tag{25}$$
$$d_1 = \frac{1}{2}\begin{pmatrix} 1 \\ 0 \\ -1 \end{pmatrix} \tag{26}$$

The **discrete gradient** is defined as

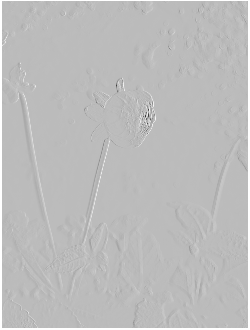
$$\nabla f = \begin{pmatrix} \partial_0 f \\ \partial_1 f \end{pmatrix}\ , \tag{27}$$

and $|\nabla f| = \sqrt{(\partial_0 f)^2 + (\partial_1 f)^2}$ is called its **magnitude**.

Linear operators

f

$f * d_0$



$f * d_1$

Linear operators

f

$\sqrt{(f * d_0)^2 + (f * d_1)^2}$

Definition 14. Let $n_0, n_1 \in \mathbb{N}$, let $V = n_0 \times n_1$ and let $C \subseteq \mathbb{R}$. Given

- a metric $d_s : V \times V \to \mathbb{R}_0^+$ and a decreasing $w_s : \mathbb{R}_0^+ \to [0,1]$
- a metric $d_c : C \times C \to \mathbb{R}_0^+$ and a decreasing $w_c : \mathbb{R}_0^+ \to [0,1]$
- a $N : V \to 2^V$ that defines for every pixel $v \in V$ a set $N(v) \subseteq V$ called the **spatial neighborhood** of v
- the $\nu : C^V \to \mathbb{R}^V$, called **normalization**, such that for any digital image $f : V \to C$ and any pixel $v \in V$:

$$\nu(f)(v) = \sum_{v' \in N(v)} w_s(d_s(v,v'))\, w_c(d_c(f(v), f(v'))) \ , \tag{28}$$

the **bilateral filter** wrt. d_s, w_s, d_c, w_c and N is the $\beta : C^V \to (\mathbb{R}C)^V$ such that for any digital image $f : V \to C$ and any pixel $v \in V$:

$$\beta(f)(v) = \frac{1}{\nu(f)(v)} \sum_{v' \in N(v)} w_s(d_s(v,v'))\, w_c(d_c(f(v), f(v')))\, f(v') \tag{29}$$

Example.

- $d_s(v, v') = \|v - v'\|_2$ and, for a filter parameter $\sigma_s > 0$:

$$w_s(x) = \frac{1}{\sigma_s \sqrt{2\pi}} \exp\left(-\frac{x^2}{2\sigma_s^2}\right) \tag{30}$$

- $d_c(g, g') = |g - g'|$ and, for a filter parameter $\sigma_c > 0$:

$$w_c(x) = \frac{1}{1 + \frac{x^2}{\sigma_c^2}} \tag{31}$$

- for a filter parameter $n \in \mathbb{R}_0^+$:

$$N(v) = \{v' \in V \mid d_s(v, v') \leq n\} \tag{32}$$

Exercise. Implementation and (recursive) application of the bilateral filter.

Definition 15. Let $n_0, n_1 \in \mathbb{N}$, let $V = n_0 \times n_1$, let $C \subseteq \mathbb{R}$ and let $N : V \to 2^V$ define for every pixel $v \in V$ a set $N(v) \subseteq V$ called the spatial neighborhood of v. The **median operator** wrt. N is the function $M\colon C^V \to C^V$ such that for any $f\colon V \to C$ and any $v \in V$:

$$M(f)(v) = \text{median } f(N(v)) \tag{33}$$

Non-linear operators

Noisy image

f

Filtered image

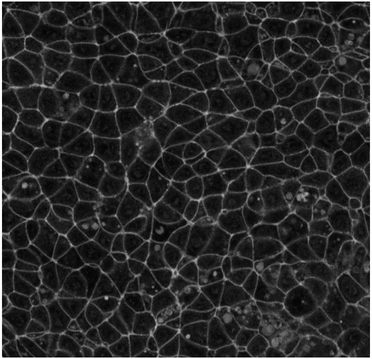
$M(f)$

Morphological operators

- We may identify any **binary** infinite digital image $f\colon \mathbb{Z}^2 \to \{0,1\}$ with its support set $f^{-1}(1) = \{v \in \mathbb{Z}^2 \mid f(v) = 1\}$.
- This allows us to apply operations from the field of **binary mathematical morphology** to binary infinite digital images.

Non-linear operators

Image[1]



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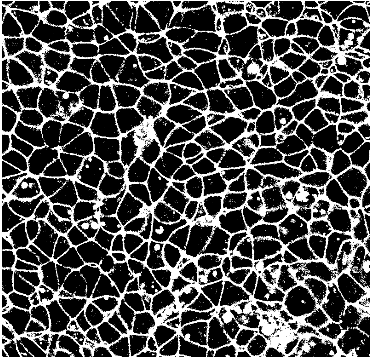
Binary image



$f \geq 45$

[1] By courtesy of Stephan Grill and his lab at the MPI of Molecular Cell Biology and Genetics.

Definition 16. A function $\otimes \colon 2^{\mathbb{Z}^2} \times 2^{\mathbb{Z}^2} \to 2^{\mathbb{Z}^2}$ is called a **morphological operation**.

Example 1. For any $A, B \subseteq \mathbb{Z}^2$:

$$A \ominus B := \{v \in \mathbb{Z}^2 \mid B + v \subseteq A\} \qquad \text{(erosion)} \qquad (34)$$

$$A \oplus B := \{v \in \mathbb{Z}^2 \mid -B + v \cap A \neq \emptyset\} \qquad \text{(dilation)} \qquad (35)$$

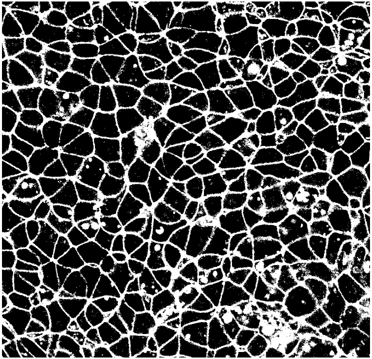
$$A \circ B := (A \ominus B) \oplus B \qquad \text{(opening)} \qquad (36)$$

$$A \bullet B := (A \oplus B) \ominus B \qquad \text{(closing)} \qquad (37)$$

Definition 17. For any (typically finite and small) $B \subseteq \mathbb{Z}^2$ called a **structuring element** and any morphological operation $\otimes$, the **morphological operator** wrt. $\otimes$ and B is defined as the $\varphi_{\otimes B} \colon \{0,1\}^{\mathbb{Z} \times \mathbb{Z}} \to \{0,1\}^{\mathbb{Z} \times \mathbb{Z}}$ such that for any (infinite binary digital image) $f \colon \mathbb{Z}^2 \to \{0,1\}$ and any (pixel) $v \in \mathbb{Z}^2$:

$$\varphi_{\otimes B}(f)(v) = 1 \quad \Leftrightarrow \quad v \in f^{-1}(1) \otimes B \ . \qquad (38)$$

Binary image



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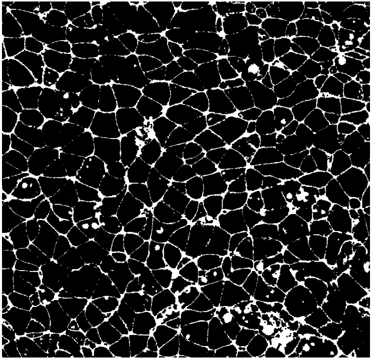
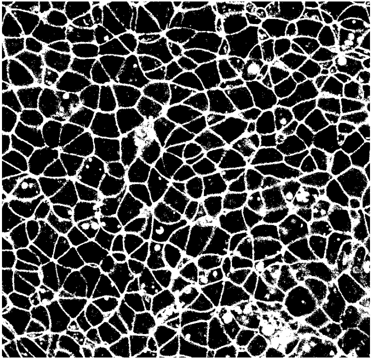
Erosion



$\varphi_{\ominus B}(f)$

Binary image



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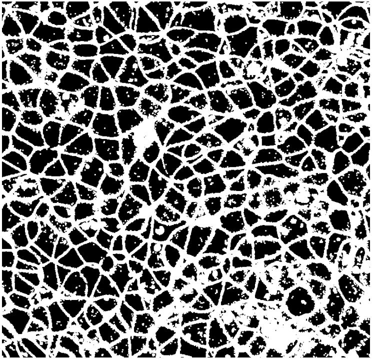
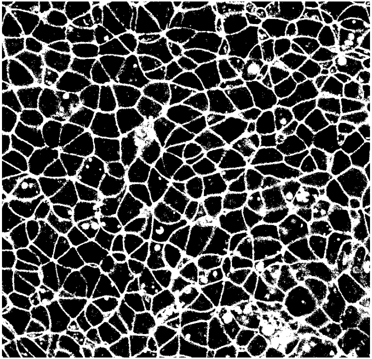
Dilation



$\varphi_{\oplus B}(f)$

Binary image



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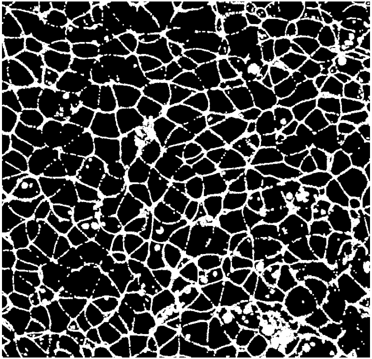
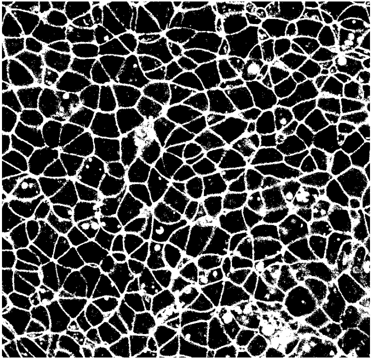
Opening



$\varphi_{\circ B}(f)$

Binary image



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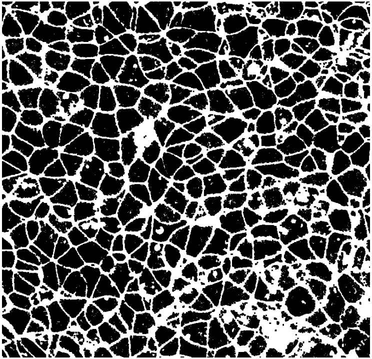
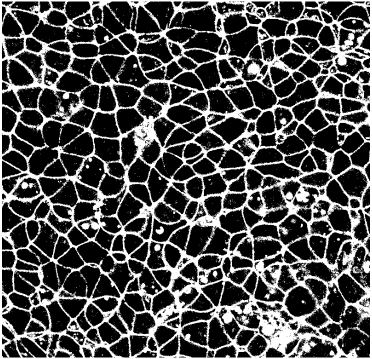
Closing



$\varphi_{\bullet B}(f)$

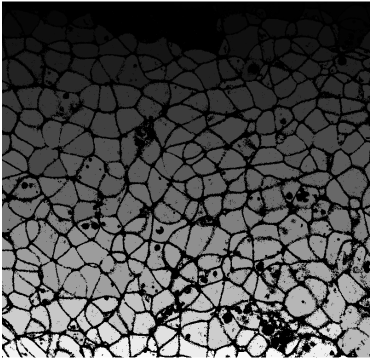
Definition 18. For any $n_0, n_1 \in \mathbb{N}$, the set $V = n_0 \times n_1$ and the pixel grid graph $G = (V, E)$, an operator $\varphi\colon \mathbb{N}_0^V \to \mathbb{N}_0^V$ is called a **(connected) components operator** if for any digital image $f\colon V \to \mathbb{N}_0$ and any pixels $v, w \in V$, we have $\varphi(f)(v) = \varphi(f)(w)$ iff there exists a vw-path in G along which all pixels have the color zero.

Binary image



f

Connected component labeling



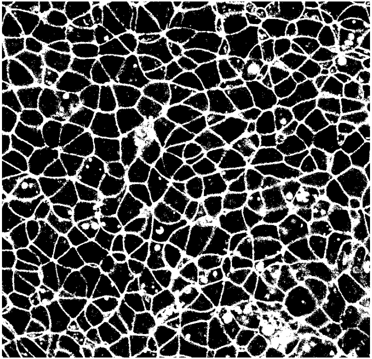
$\varphi(f)$

Non-linear operators

```
size_t componentsImage(
    Marray<size_t> const & image,
    Marray<size_t> & components
) {
    components.resize({image.shape(0), image.shape(1)});
    PixelGridGraph pixelGridGraph({image.shape(0), image.shape(1)});
    size_t component = 0;
    stack<size_t> stack;
    for(size_t v = 0; v < pixelGridGraph.numberOfVertices(); ++v) {
        Pixel pixel = pixelGridGraph.coordinate(v);
        if(image(pixel[0], pixel[1]) == 0
        && components(pixel[0], pixel[1]) == 0) {
            ++component;
            components(pixel[0], pixel[1]) = component;
            stack.push(v);
            while(!stack.empty()) {
                size_t const v = stack.top();
                stack.pop();
                for(auto it = pixelGridGraph.verticesFromVertexBegin(v);
                it != pixelGridGraph.verticesFromVertexEnd(v); ++it) {
                    Pixel pixel = it.coordinate();
                    if(image(pixel[0], pixel[1]) == 0
                    && components(pixel[0], pixel[1]) == 0) {
                        components(pixel[0], pixel[1]) = component;
                        stack.push(*it);
                    }
                }
            }
        }
    }
    return component; // number of components
}
```

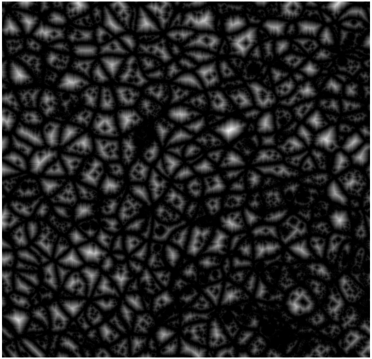
Definition 19. For any $n_0, n_1 \in \mathbb{N}$, the set $V = n_0 \times n_1$ and the pixel grid graph $G = (V, E)$, the **distance operator** $\varphi\colon \mathbb{N}_0^V \to \mathbb{N}_0^V$ is such that for any digital image $f\colon V \to \mathbb{N}_0$ and any pixel $v \in V$, the number $\varphi(f)(v)$ is the minimum distance in the pixel grid graph from v to a pixel w with $f(w) \neq 0$.

Binary image



f

Distance image



$\varphi(f)$

Non-linear operators

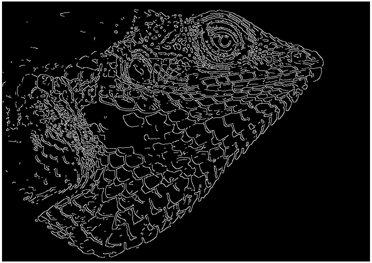
```cpp
size_t distanceImage(
    Marray<size_t> const & image,
    Marray<size_t> & distances
) {
    distances.resize({image.shape(0), image.shape(1)}, 0);
    GridGraph pixelGridGraph({image.shape(0), image.shape(1)});
    size_t distance = 0;
    array<stack<size_t>, 2> stacks;
    for(size_t v = 0; v < pixelGridGraph.numberOfVertices(); ++v) {
        Pixel pixel = pixelGridGraph.coordinates(v);
        if(image(pixel[0], pixel[1]) != 0)
            stacks[0].push(v);
    }
    ++distance;
    for(;;) {
        auto & stack = stacks[(distance - 1) % 2];
        if(stack.empty())
            return distance - 1; // maximal distance
        while(!stack.empty()) {
            size_t const v = stack.top();
            stack.pop();
            for(auto it = pixelGridGraph.verticesFromVertexBegin(v);
            it != pixelGridGraph.verticesFromVertexEnd(v); ++it) {
                Pixel pixel = it.coordinate();
                if(image(pixel[0], pixel[1]) == 0
                && distances(pixel[0], pixel[1]) == 0) {
                    distances(pixel[0], pixel[1]) = distance;
                    stacks[distance % 2].push(*it);
                }
            }
        }
        ++distance;
    }
}
```

For any set V of pixels and neighborhood function $N\colon V \to 2^V$, **non-maximum suppression** is the operator $\varphi_{\mathrm{NMS}}\colon \mathbb{R}^V \to \mathbb{R}^V$ such that for each digital image $f\colon V \to \mathbb{R}$ and all pixels $v \in V$:

$$\varphi_{\mathrm{NMS}}(f)(v) = \begin{cases} f(v) & \text{if } f(v) = \max f(N(v)) \\ 0 & \text{otherwise} \end{cases} \tag{39}$$

Image[1]

Edge detection[1]



[1] https://en.wikipedia.org/wiki/Canny_edge_detector

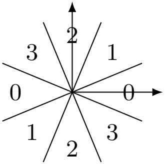
Canny's edge detection algorithm[1] has four steps

1. Gradient computation from digital image $f\colon V \to \mathbb{R}$:

$$g = \sqrt{\partial_0 f + \partial_1 f} \qquad \texttt{std::hypot} \text{ in C++} \tag{40}$$

$$\alpha = \operatorname{atan2}(\partial_1 f, \partial_0 f) \qquad \texttt{std::atan2} \text{ in C++} \tag{41}$$

2. Directional non-maximum suppression of g:



3	2	1
0		0
1	2	3

3. Double thresholding with $\theta_0, \theta_1 \in \mathbb{R}_0^+$ such that $\theta_0 \leq \theta_1$: A (any) pixel $v \in V$ is taken considered to be a **strong edge pixel** iff $\theta_1 \leq g(v)$ and is taken to be a **weak edge pixel** iff $\theta_0 \leq g(v) < \theta_1$.

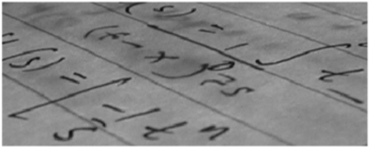
4. Weak edge classification: A (any) pixel $v \in V$ is taken to be an **edge pixel** iff (i) v is a strong edge pixel, or (ii) v is a weak edge pixel and there is a strong edge pixel in the 8-neighborhood of v.

---

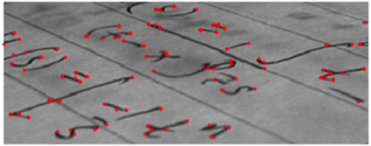
[1] J. Canny. A Computational Approach To Edge Detection. IEEE Transactions on Pattern Analysis and Machine Intelligence, 8(6):679–698, 1986

Edge and corner detection

Image[1]



Corner detection[1]



[1] https://en.wikipedia.org/wiki/Corner_detection

Definition 20. Let $n_0, n_1 \in \mathbb{N}$, let $V = n_0 \times n_1$, let $f\colon V \to \mathbb{R}$ a digital image, let ∂_0, ∂_1 be discrete derivative operators, and let $N\colon V \to \mathbb{R}^V$.

For each $v \in V$:

- Let $A(v)$ be the $N(v) \times 2$-matrix such that for every $w \in N(v)$:

$$A_{w\cdot}(v) = ((\partial_0 f)(w), (\partial_1 f)(w)) \ . \tag{42}$$

- Let $k_v\colon N(v) \to \mathbb{R}_0^+$ such that $\sum_{w \in N(v)} k_v(w) = 1$.
- Define the **structure tensor** of f at v wrt. k_v as the 2×2-matrix

$$S_k(f)(v) := \sum_{w \in N(v)} k_v(w) A^T_{w\cdot}(v) A_{w\cdot}(v) \tag{43}$$

$$= \sum_{w \in N(v)} k_v(w) \begin{pmatrix} (\partial_0 f)^2(w) & (\partial_0 f)(w)(\partial_1 f)(w) \\ (\partial_0 f)(w)(\partial_1 f)(w) & (\partial_1 f)^2(w) \end{pmatrix} \ . \tag{44}$$

Remark 1. Fix a direction by choosing $r \in \mathbb{R}^2$ with $|r| = 1$ and consider the k_v-weighted squared projection of the gradient of the digital image:

$$\begin{aligned} P_r(v) &= \sum_{w \in N(v)} k_v(w) |A_{w\cdot}(v)\, r|^2 &(45)\\ &= \sum_{w \in N(v)} k_v(w)\, r^T A_{w\cdot}^T(v) A_{w\cdot}(v)\, r &(46)\\ &= r^T \left(\sum_{w \in N(v)} k_v(w) A_{w\cdot}^T(v) A_{w\cdot}(v) \right) r &(47)\\ &= r^T S(v)\, r &(48)\end{aligned}$$

With the spectral decomposition

$$S(v) = \sigma_1(v) s_1(v) s_1^T(v) + \sigma_2(v) s_2(v) s_2^T(v) \tag{49}$$

we obtain

$$\begin{aligned} P_r(v) &= r^T \left(\sigma_1(v) s_1(v) s_1^T(v) + \sigma_2(v) s_2(v) s_2^T(v) \right) r &(50)\\ &= \sigma_1(v) |s_1(v) \cdot r|^2 + \sigma_2(v) |s_2(v) \cdot r|^2 \ . &(51)\end{aligned}$$

Remark 2.

- If $\sigma_1 = \sigma_2 = 0$, we have $P_r(v) = 0$ for any direction r. I.e. the image is constant.
- If $\sigma_1 > 0$ and $\sigma_2 = 0$, we can choose a direction r such that $P_r(v) = 0$. I.e. the gradient of the image is non-zero and constant.
- If $\sigma_1, \sigma_2 > 0$, we cannot choose r such that $P_r(v) = 0$. I.e. the gradient of the image varies across $N(v)$.

Definition 21. Let V the set of pixels of a digital image, let $S\colon V \to \mathbb{R}^{2\times 2}$ such that for any $v \in V$, $S(v)$ is the structure tensor of the image at pixel v, and let $\sigma_1(v) \geq \sigma_2(v) \geq 0$ be the eigenvalues of $S(v)$. **Harris' corner detector**[2] wrt. a neighborhood function $N\colon V \to 2^V$ refers to the function $\varphi_{\mathrm{NMS}} \circ \sigma_2$.

[2] C. Harris and M. Stephens. A Combined Corner and Edge Detector. Alvey Vision Conference. Vol. 15. 1988